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Design and characterization of an ultrasonic surgical tool using d_{31} PMN-PT plate

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Abstract

An ultrasonic surgical tool for tissue incision and dissection has been designed and characterized. The surgical tool is based on a simple geometry to which PMN-PT d_{31} plates are bonded directly. The performance of the surgical tool has been defined numerically with the Abaqus finite element analysis (FEA) package and practically with laser vibrometer and impedance spectroscopy. The results show the ability of FEA to accurately predict the behaviors of an ultrasonic device as numerical and practical analysis were found to be in a good agreement. The design of the tool presented has the ability to generate displacement amplitude high enough to carry out soft tissue incision with relatively low driving voltage.

Peer-review under responsibility of the Ultrasonic Industry Association

Keywords: Ultrasonic cutting, PMN-PT, soft tissue cutting;

1. Introduction

Ultrasonic surgical devices have been widely used in surgical operations for biological tissue dissection. These devices usually consist of a piezoelectric transducer to generate ultrasonic waves, a horn to amplify the vibration amplitude and a blade to interact with tissue. The longitudinal oscillation of this blade leads to the mechanical cutting of tissue.

Many advantages of ultrasonically activated tissue dissection have been reported. These include less bleeding, less postoperative complication (Schmidbauer, Hallfeldt et al. 2002), less lateral thermal damage (Gossot, Buess et al. 1999), precise and fast operation using relatively low forces (Lucas, Cardoni et al. 2005). Moreover, compared to

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electro-cautery or laser scalpel, advantages of ultrasonic surgical tools such as smoke-free and no current flow through the patient have also been recognized in endoscopic surgery (Koch, Friedrich et al. 2003). During the last a few decades, attempts have been repeatedly made to improve the performance of the ultrasonic surgical devices and many of them are commercial available for clinically uses (O'Daly, Morris et al. 2008).

Traditionally, the ultrasonic surgical devices are based on a sandwich piezoelectric transducer as shown Fig. 1, which often operates in d_{33} mode of Lead Zirconate Titanate (PZT) material. The d_{33} mode, i.e. Length Extensional (LE) mode, means the piezoelectric material is poled in the thickness direction while it vibrates in the same direction, as in the bar shown in Fig. 2.

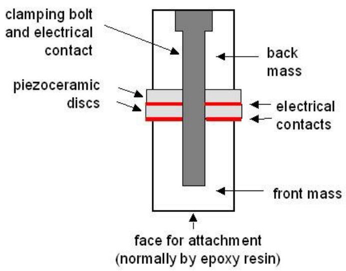

Fig.1 typical structure of a sandwich piezoelectric transducer

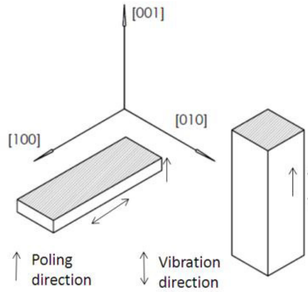

Fig. 2 d_{33} and d_{31} vibration mode of piezoelectric materials

These type of ultrasonic tools with PZT in d_{33} mode although show effectiveness in many applications due to the large displacement amplitude which can be generated at the tip of the tool, there exist some factors which limit their scope of applications. These factors include large size of the tool and high driving voltage which is required to generate the desired results (Lal and White 1995).

This paper overcomes these limitations by adapting the design concept from (Lal and White 1995) while replacing the PZT material with lead magnesium niobate-lead titanate (PMN-PT) operating in d_{31} mode. Vibration mode d_{31}, or called Length-Thickness Extensional (LTE) mode means the poling direction is [001] while the vibration direction is [100], as the plate shown in Fig. 2. A schematic of the proposed design is shown in Fig. 3. Two plates of PMN-PT operating in d_{31} mode are bonded onto a stainless steel blade symmetrically to drive the blade. In order to clamp the surgical tool two bridges are created at the nodal plane of the blade.

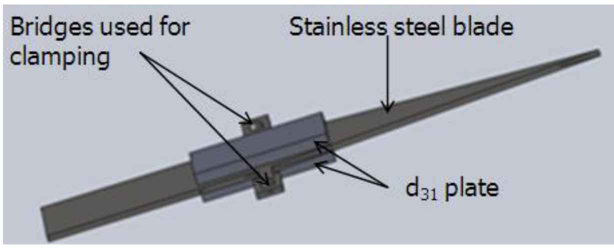

Fig. 3 Proposed surgical tool

The proposed design operates similarly with the conventional one. The two piezoelectric plates change the electrical energy into mechanical energy while the sharp shape of the blade concentrates the energy to make sure a displacement large enough at the tool tip. However, as the piezoelectric coefficient of PMN-PT d_{31} (1338 pC/N) is much higher than that of PZT d_{33} (255 pC/N) (Kim, Kim et al. 2006, Hana, Marina et al. 2011), lower voltage is required to generate desired displacement at the tool. Moreover, as high driving voltage leads to rise in temperature dramatically within the transducer and at the tip of the tool, which may damage the surrounding tissue, this apply of lower voltage can reduce the thermal effects to certain extent.

2. Design and Fabrication Procedure

2.1. Design of Ultrasonic Surgical Tool

The piezoelectric material to be used for exciting the blade is PMN-PT plate in d_{31} mode. Impedance rest result shows that it has a resonant frequency of 73.01 KHz. In order to ensure the effective motion of the surgical tool at the resonance frequency, the blade is designed to be resonant in longitudinal mode at the resonant frequency of the d_{31} plate. This designing process of surgical tool was conducted in commercial finite element analysis software—Abaqus, which was used to extract the resonant frequencies and simulate the modal shape.

The initial shape of the blade is shown in **Error! Reference source not found.**(a). The modal shape analysis indicates the blade longitudinally resonant at 73.05 KHz. Then in order to clamp the blade, two bridges with holes are created along the nodal plane and the blunt side of the blade was modified to be rectangle for easy manufacture, as shown in **Error! Reference source not found.**(b). The blade was then further modified to the final shape as shown in **Error! Reference source not found.**(c) to reduce the vibration of the bridges. The resonant frequency is 73.36 KHz and the normalized longitudinal displacement along the length of the blade is shown in **Error! Reference source not found.**.

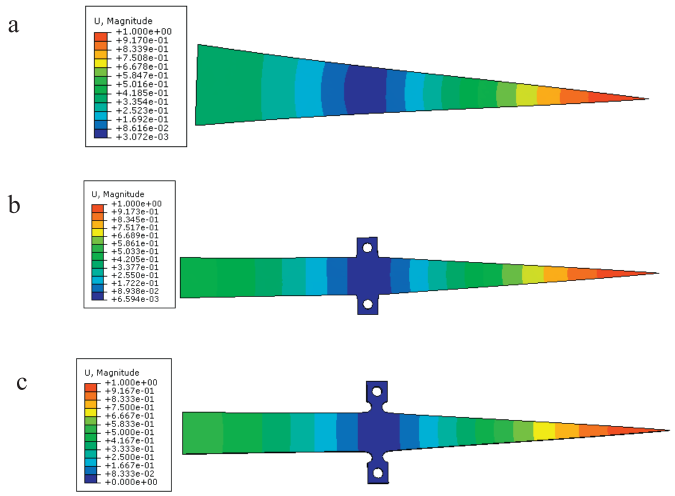

Fig. 4 Design process (a) initial design (b) blade with brides (c) final design

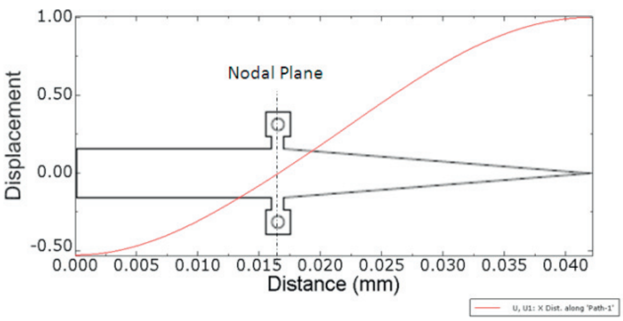

Fig. 5 Normalized displacement along the tool length

The PMN-PT d_{31} plate was then bonded onto the blade, the nodal plane of which is aligned with that of the PMN-PT plate. The bonding of the blade and PMN-PT plate was achieved by ‘tie constrain’ in the Interaction Module of

Abaqus. The PMN-PT was defined as orthotropic material and the material properties were obtained from previous study(Z.Qiu, M.R.Sadiq et al. 2011). Simulation shows that the surgical tool longitudinally resonant at 73.5 KHz. However, as it can be seen from **Error! Reference source not found.**(a), this mode is a combination of longitudinal and flexural modes. This is mainly because the tool plate was not driven symmetrically about the blade plane. This bending mode can be almost fully eliminated by bonding another PMN-PT plate symmetrically onto the other side of the blade, which is shown in **Error! Reference source not found.**(b). In this case, the resonant frequency of the surgical tool rises to 73.749 KHz.

As cutting blades can easily fail due to the stress level generated by driving thin blades at high amplitudes, stress analysis of the surgical tool was performed by applying 1 volt peak-to-peak harmonic voltage to both PMN-PT plates. The Mises Stress distribution obtained from Abaqus is illustrated in **Error! Reference source not found.**. The maximum stress is 1.25 MPa, which is believed to increase linearly with the voltage applied within the linear response range of the piezoelectric material. As the low voltage required for the PMN-PT material, the maximum stress was kept within elastic deformation range of the stainless steel. In addition, although the stepped edge of the bridge introduces stress concentration, however, as it is located close to the nodal plane and relatively away from the d_{31} plates, the bridge doesn't experience any high stress concentration.

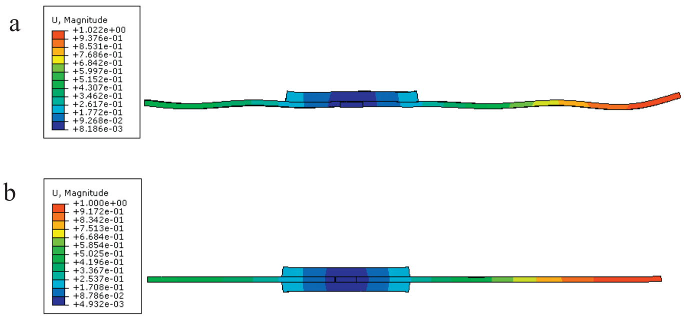

Fig.6 Longitudinal modal shape of the surgical tool (a) blade with one d_{31} plate bonded (b) blade with two d_{31} plates bonded symmetrically

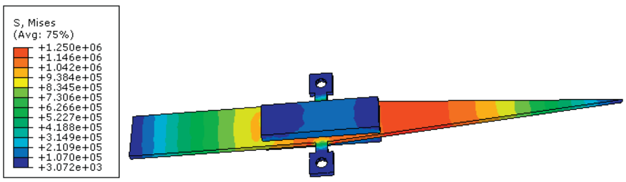

Fig. 7 Von Mises stress distribution of the surgical tool

2.2. Fabrication of Ultrasonic Surgical Tool

The fabrication process initiated with the attachment of the piezoelectric material onto the blade. The PMN-PT plate was bonded on at the nodal plane of the blade using conductive epoxy (EJ2189-LV, Epoxy Technology, USA), which provides good electrical conductivity, good mechanical adhesive strength, and resistance to piezoelectric vibration. In addition, silver epoxy (Agar Scientific Ltd., Essex, UK) was used to bond the lead wires on the surface of the d_{31} plate and the blade which served as a ground connection.

A holder was designed to clamp the surgical tool by bolts through the holes on the bridges. The fabrication process is shown in Fig. 8. Currently, only one d_{31} plate is bonded onto the blade. After being fully characterized, another plate will be attached in the future.

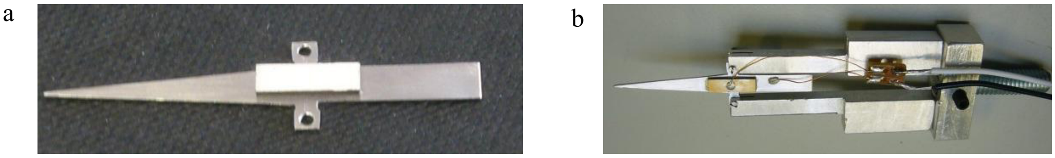

Fig. 8 Fabrication of the surgical tool (a) d_{31} plate is bonded to the blade (b) wires are connected and a holder is assembled

3. Characterization

3.1. Electrical Characterization

The tool was characterized at different stages of fabrication using an HP 4395A impedance / network / spectrum analyzer (Agilent Technologies, South Queensferry, UK) operated in impedance analysis mode. The impedance vs. frequency plots were obtained to observe changes in impedance and other modes which were expected due to the change in structure.

As can be seen from **Error! Reference source not found.**(a), the PMN-PT plate shows a resonant frequency at 73.01 KHz with an impedance of 132 Ohms. With one d_{31} plate bonded, the surgical tool shows rises in resonant frequency and impedance, which are 73.637 KHz and 285 Ohms respectively, shown in **Error! Reference source not found.**(b).

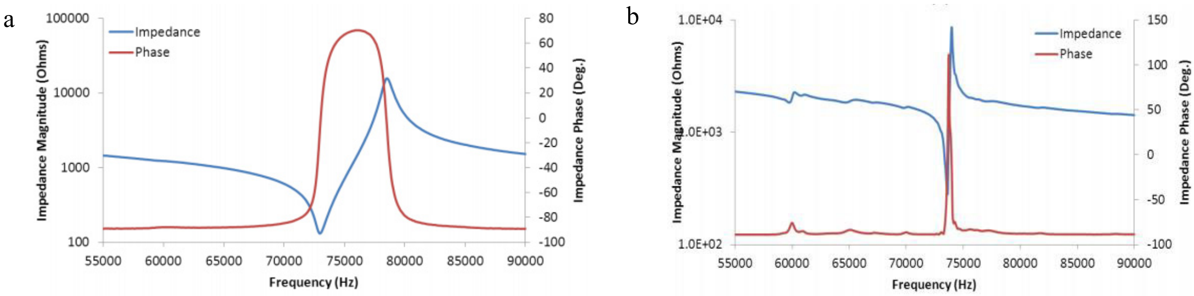

Fig. 9 Impedance Vs Frequency plots (a) PMN-PT plate (b) blade with one d_{31} plate bonded

Ideally, an impedance matching circuit is needed to meet the specification of impedance matching and thus to improve the power transformation. However, as the use of the conductive epoxy, the impedance of the surgical tool is relatively low, and with another d_{31} plate bonded the impedance of the surgical tool is expected to reduce, thus, the impedance matching was not included at the stage of characterization.

3.2. Mechanical Characterization

The mechanical characterization was carried out through the measurement of displacement using a single-point laser vibrometer (Polytech OFV- 534 & OFV-2570). The laser vibrometer utilizes Doppler Effect of the laser to detect the velocity or displacement of the out-of-plane vibration which are transformed to voltage signals. These voltage signals were sampled by a digitizer PXIe 5122 (National Instruments Corporation UK). The experimental setup is shown in **Error! Reference source not found.**, which includes the function generator 33220A (Agilent technologies, UK) and RF power amplifier (E&I Ltd. USA) to supply driving voltage.

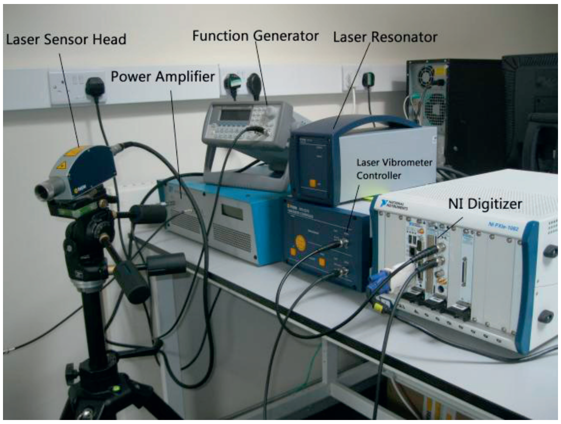

Fig. 10 Setup for mechanical characterization

The longitudinal displacement measurements were carried out at the tool tip and at the side of the bridge, which is 0.5 mm away from the nodal plane. As can be seen from **Error! Reference source not found.**, the longitudinal displacement at the tool tip increases linearly with the voltage amplitude. As expected, the displacement on the bridge side is close to zero, which implies that it is close to the nodal plane of the surgical tool.

The flexural displacement at tool tip was also measured to derive the local modal shape and validate the prediction of Abaqus. **Error! Reference source not found.** shows relatively big flexural displacement at the tool tip. The averaged ratio of longitudinal and flexural displacement is about 4.26, which is close to the value of 4.37 predicted by simulation in Abaqus.

The longitudinal displacement response at different frequencies was also measured by using laser vibrometer while applying frequency-swept harmonic voltage to the surgical tool. **Error! Reference source not found.** illustrates the frequency response of the surgical tool at the tool tip from 50 KHz to 90 KHz. As can be seen from the Fig., the surgical tool exhibits a longitudinal resonance at around 73.6 KHz and another resonance with much lower amplitude at around 60 KHz, which were identified by the impedance curve in **Error! Reference source not found.**(b) as well.

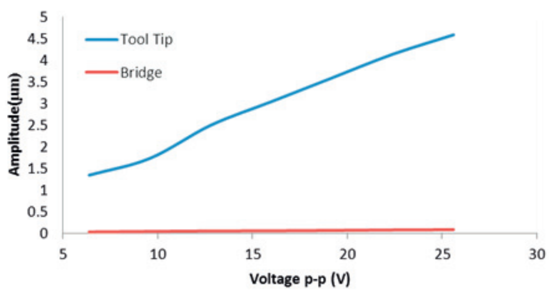

Fig . 11 Longitudinal displacement

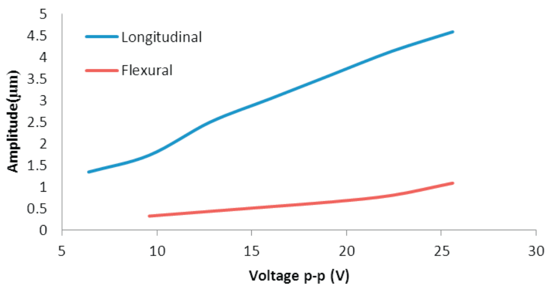

Fig. 12 Longitudinal and flexural displacement at tool tip

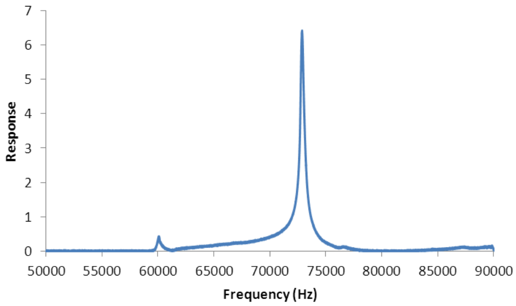

Fig. 13 Frequency response of the surgical tool in longitudinal direction

4. Conclusion and Future Work

An ultrasonically driven surgical tool was designed, fabricated and characterized successfully. The design and simulation were conducted in Finite Element Analysis software Abaqus while the experimental characterization of the fabricated surgical tool was performed using impedance analyzer and laser vibrometer.

The surgical tool comprises of a stainless steel blade, the shape of which is designed to be easy for manufacturing and clamping while maintain sharp tip. A PMN-PT d_{31} plates was bonded onto the blade to drive the surgical tool. As the high piezoelectric coefficient of PMN-PT, the voltage needed to drive the surgical tool is reduced. The surgical tool showed high performance in terms of longitudinal displacement amplitude. Though with only one d_{31} plate bonded, the surgical tool exhibits serious flexural displacement at longitudinal resonant frequency, which is predicted precisely by simulation and validated by experiment, the simulation in Abaqus showed this flexural mode can be eliminated by attaching another d_{31} plate to the blade symmetrically.

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